HB MORPHOLOGY AND THE SECOND PARAMETER EFFECT: FAINT STARS IN A BIG GAME

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ABSTRACT: We schematically review some of the main steps in the study of the Horizontal Branch Morphology in Galactic Globular Clusters. Since the first realization of the existence of the so-called *Second Parameter Problem* ($2^{nd}P$) up to now, one could perhaps see a sort of circular path. Actually, many candidate $2^{nd}P$'s were proposed during the early '70s, *age* has been *the* top-scored $2^{nd}P$ during the late '80s, and we are now back to even more candidates, including also possible intriguing combinations of some of them.

1.   Introduction

As a great movie star, the horizontal branch (HB) of globular clusters has been on stage for more than four decades, playing an obvious major rôle in many astrophysical "big games", like the distance scale and the lower limit to the age of the universe. Nevertheless, many fundametal aspects about origin and evolution of HB stars themselves are still wrapped up behind a thick smokescreen. Many valuable investigators have joined their efforts to unveil such a curtain, finding a lot of important clues (sometimes confusing, indeed), but very few clear-cut and solid conclusions have been drawn on many relevant aspects so far. In particular, *firm* evidences and conclusions adopted as *cornerstones* for some years, suddenly turned out to be *friable* or even misleading.

Despite their relative faintness, HB stars are implicated in several astrophysical basic questions. Looking at a typical color-magnitude diagram (CMD), the comprehension of their distribution is fundamental both in the *vertical* sense, (*i.e.* luminosity: connected to distance and age scales, etc.) and in the *horizontal* sense, (*i.e.* temperature: connected

to mass loss, integrated colors of distant stellar populations, etc.).

Here we briefly deal with this latter issue, *i.e.* the HB morphology –the color (temperature) distribution of HB stars– in Galactic globular clusters (GGCs), often also referred to as the *Second Parameter Problem* –($2^{nd}P$). We provide a very schematic (and necessarily biased) reference table on about forty years of investigations, starting from the pioneering photographic works up to the latest studies carried out with HST, which leave us with the uncomfortable evidence that one of the most prominent features in the GGC CMDs is probably still one of the less understood phases of the evolution of Pop. II stars (see for instance the CMDs presented in these proceedings by Liebert et al. and Ferraro et al. showing HB's with 2-3 gaps).

To follow a sort of (admittedly biased) chronological path a parallel consultation of Table 1 may be useful, where just a few "reference" references can be found. We apologize for any unforgivable omission.

2.   Realizing that the HB-morphology world is not so simple...

Though Shapley (1919) already had some suspicion, the realization of the existence of a $2^{nd}P-problem$ in the classification of the observed HB morphologies in GGCs came out in the early '60s. In fact, the conclusion was: metallicity – Z – is the *first* parameter; since however GGCs with similar metallicities have *different* HBs, a *second* parameter must exist, which originates the differences.

Important efforts to compute the first HB theoretical models and to yield a systematic parametrization of the observed HBs were made during the early '70s. One can easily ascertain that the essence of the problem was already set on clear grounds at that time (see, in particular, Rood 1973), and various $2^{nd}P-candidates$ were proposed (helium abundance, age, CNO). Four items were especially noted, and frequently forgiven later:

• *The HB is not an evolutive sequence, but simply a narrow, composite locus, like "a beach, where all stars go to take a bath".*

• *Mass loss is the crucial phenomenon and parameter which drives the actual location of the HB in color.* In particular, *"why, when, where, how much, and how long mass loss does take place before the HB matters very much".*

• *The (color) temperature shift along the Zero Age HB is strongly dependent on mass loss and is highly non-linear with varying metallicity,* $\Delta T_{eff} = f(\Delta M_{loss}, Z)$.

• *Any mechanism (intrinsic or induced) which could somehow affect, during any evolution-ary stage, the core and/or total mass of the star may play a rôle in the $2^{nd}P-game$ because of the exceptional sensitivity of HB stars to any tiny variation.*

2.1.   Exotica enter into the game

With the growing discoveries of peculiarities in the chemical abundances of GGC stars and the existence of gaps and special features along the main branches in the CMD (including the HB), it became clear during the next decade ('73 – '83) that the interpretation of the HB morphology could not be so *simple* as most of the players could hope. Other $2^{nd}P$'s were proposed (in particular, core rotation). It was also evident that most of the observed chemical peculiarities could not be explained just by *primordial* abundance variations, but that also special mixings have to take place in the stars (see Kraft 1979, and Table 1).

At the end of that decade, in the attempt to explain the "curious" couple of very metal-poor clusters M15–NGC5466, we (Buonanno et al. 1985) naively proposed to ascribe their stricking different HB-morphologies to the very different *stellar density* within their central regions. Though hard to quantitatively estimate to what extent and how such a new ingredient could play a significant rôle in the $2^{nd}P-problem$ (but surely via "induced" extra mass-loss), this idea built up a possible new bridge between stellar evolution and stellar dynamics.

3.   ...and, somehow, forgetting it...

In 1986, but actually starting from the fundamental papers by Searle and Zinn (1978–SZ) and Zinn (1985), through the use of the new index $B - R/B + V + R$ – with B, V, R =number of blue, variable, red HB stars– and of the overall description of the GGC system proposed by Zinn (1986), two basic conclusions were achieved:

• The $2^{nd}P$-effect presents a quite strong dependence on Galactocentric distance, with redder HB's predominantly found in the outer regions of the Milky Way.

• Since the most obvious way of producing redder HB's for fixed metallicity is that of increasing the total mass (at constant core mass and total mass loss), and since by decreasing the cluster age one automatically yields larger initial (TO) masses, the above evidence has been *adopted* to be a clear-cut evidence that (a) *age is the Second Parameter*, and (b) at given metallicity, *redder HB's imply younger age.* Hence, the HB-morphology could actually be used as a *clock*.

While the interpretation of the *global* scenario has probably been one of the most exciting and profitable steps in the description of formation and evolution of our own Galaxy (and even of galaxies, in general), there has also been a sort of "bouncing-back" effect leading to conclude that: since the adoption of age as *the only (dominant)* $2^{nd}P$ allows us to build up a nice overall description of the Galaxy, then the $2^{nd}P-problem$ is solved. In our opinion, this was –and still is– not true.

3.1.   Global and non-global $2^{nd}P$'s

During the late '80s, the idea that the age is by far the *dominant* parameter was corroborated by many observations (see Table 1). At the same time, however, also the detection of both photometric and spectroscopic peculiarities was growing up steadly, and the need for the distinction between the so-called *global* and *non-global* $2^{nd}P$'s, proposed first by Freeman and Norris (1981), became obvious though not unequivocal. In fact, for instance Freeman and Norris assumed as *global* the parameters which affect all the stars in a cluster at the same extent; Lee (1993) defined as *global* the $2^{nd}P$ which originates the dependence of the index $B-R/B+V+R$ on Galactocentric distance; we (Buonanno et al. 1985, Fusi Pecci 1987–$2^{nd}Conf.FBS$) interpreted the definition of *global* to mean that the parameter driving the HB morphology is actually the result of the "global combination" of many individual quantities and phenomena affecting the evolution of a single star in a cluster or even the cluster as a whole.

3.2.   Age at the apex, but ....

The scenario proposed first by Searle and Zinn (1978) has been very interestingly refined during the early '90s. And the idea that age is *the* $2^{nd}P$ reached its apex in popularity. Meanwhile, for the first time, *young* Galactic globular clusters have actually been found (see Table 1), using measurements based on the MS-TO. Note that, due to the still too large uncertainties affecting all age determinations (even *relative*), only for a very small sub-set of GGC's there is a sufficiently reliable evidence that they are actually *younger* than the bulk of clusters having similar metallicities. Since these *young* globulars seem to be members of the Sgr dwarf falling onto the Galaxy central regions, we are probably observing a "real-time" confirmation of the *building block accretion*, as envisaged by SZ.

But the questions are: (1) *What fraction of the halo is actually young? How big is the age difference? Where and how was this young component orignated?*, and (2) *Do the other globulars, presumably not involved in these "interacting connections", actually*

show reliably significant age differences? Moreover, (3) *Are we still allowed to include all the detected special features just within the non-global box?* They are actually increasing in type and number, and "exceptions" are becoming "the rule".

4. ... problems come back, ...

The results obtained in the latest years, especially thanks to HST–observations in the very central regions of the clusters and for Galactic globulars located in the inner bulge or at the outskirts of the Milky Way, have shown that the interpretation of the $2^{nd}P$–effect as due only to age cannot survive (see Table 1). Detailed discussions on these new results and issues can be found in the recent reviews by VandenBerg et al. (1996), Stetson et al. (1996), Richer et al. (1996), Buonanno et al. (1997–AJ subm.).

4.1. ... and Exotica rise again

Three pieces of evidence, at least, are in fact blowing up (again):

• The HB-morphology of many clusters, especially if the very central regions are observed, is very complex. Many clusters display clearly bimodal distributions in color, there are clumps and gaps (f.i. in NGC 1851, 2808, 6388, M 13, etc.), and the description of the observed HB population and morphology with just one observational parameter is clearly inadequate.

• There is a growing evidence that significant populations of binaries or binary descendants (primordial, collisional, mergers. etc.) are present probably in almost any cluster. Moreover, internal radial gradients in color, star population, and mass distribution testify the importance of cluster dynamical evolution, which may strongly affect also the individual star evolution.

• Coupled with many renewed efforts in model computation, the increasing pattern of information on chemical abundances for many stars in several clusters obtained from high resolution spectroscopy suggests (more and more convincingly) that mixing phenomena actually take place in most stars in GGCs, and possibly at a different extent from star-to-star. For instance, Sweigart (1996–preprint) has shown that important variations in the helium abundance (a possible $2^{nd}P$) can be originated before the HB phase because of mixing, possibly somehow coupled with rotation.

5.   Are we back to the 1973 status?

It is hard to answer as we could say: Yes, after the latest evidences we are back to play with too many $2^{nd}P$–candidates. On the other hand, such a statement would be too strong as we now know that the HB-morphology presents different properties and points out different features depending on the observable adopted to describe it, as well as any astronomical object may look very different depending on the bandwidth adopted to observe it. This implies that we must look at the HB-morphology and, in particular, at the $2^{nd}P$–problem within a *global* approach, i.e. recalling that the HB-morphology is in a sense *the final convolution of many different ingredients*. We must first deconvolve the individual contributions before ranking their importance in a given cluster.

Due to shortage of space, appropriate references can be found in the few quoted papers in Tab. 1.

Table 1 - The 2nd Parameter Problem: some (admittedly biased) highlights

years	reference	clue
'19	Shapley	M3 - M13 different RR's + HB's?
'52 −' 59	Arp, Baum, Kinman, Sandage	M3 - M92 different RR's + HB's
'60	Sandage, Wallerstein	[Fe/H] is the first Parameter M13, M22 too blue for their metals
'65 −' 67	van den Bergh Sandage, Wildey	M3,M13, NGC 7006 etc. $2^{nd}P$: age? Helium?
'66 −' 69	Faulkner, Iben, Rood, Castellani, Giannone, Renzini	first HB models; $2^{nd}P$: [CNO/Fe]? mass loss is crucial
'72	Dickens	HB-types: 1-7, non-monotonic with [Fe/H]
'72	Zinn	spectr. peculiarities anomalous cepheids (V19 in NGC 5466)
'73	Mironov	HB-types: B/B+R, a quantitative HB-index
'73	Rood, ApJ 184,815	HB-syntethic models with mass loss $2^{nd}P$ Candidates: Helium Abundance, Age, [CNO/Fe]
'73	Newell	HB gaps?? in the field?

tab. 1 - continued

years	reference	clue
'73	Cannon, Lee	NGC 6752: HB blue tail + gap
'74 −' 75	Harris	NGC 2808: bimodal HB + with wide gap
'75	Reimers	mass loss rate: basic formula
'76	Mengel, Gross	models with (core) rotation
'77	Renzini	$2^{nd}P$ Candidate: core rotation
'78 −' 80	Searle, Zinn, ApJ 225,357	HB-Morphology varies systematically with Galactocentric distance $2^{nd}P$: = Age
'79	Sweigart, Mengel	meridional circulation $-->$ mixing
'79	Kraft, ARAA 17,309	review: chemical peculiarities et al.
'79 −' 83	Norris, Smith, Pilachowski, Wallerstein, Kraft, Sneden, Gratton, Bell, Kurucz, et al.	abundance: individual elements variations + correlations, etc. models etc.
'79 −' 85 '81	Cohen, Frogel, Pilachowski, Zinn, West, Peterson, Kraft, Sneden, Gratton, Hesser, Bell, et al. Freeman, Norris, ARAA 19,319 Suntzeff	abundance scale: wide and hot debate integr. phot.; high vs. low res. HB bimodality, CN, ellipticity, etc. rotation, etc., peculiarities $2^{nd}P$: "global" vs. "non-global"
'81	Grindlay, Bailyn, etal.	HB-tail: (ex-)binaries ??
'81	Castellani, et al.	HB-tail: RGB-manque' ??
'81 −' 83	Van Albada, De Boer, Dickens Caloi, Castellani et al.	UV-properties: EB, B, I, R
'81 −' 93	Sandage Cacciari, Caputo, et al.	Period-shift effect + Oosterhoof dichotomy etc.
'83	Buzzoni et al.	Helium: constant in Galactic GCs? (Iben 1968: R-method)
'83	Castellani, Renzini	HB: non-monotonic behaviour $-->$ different metallicity regimes

tab. 1 - continued

years	reference	clue
$'83 - '87$	Buonanno, Corsi, FusiPecci A&A 145,97	M15 vs. NGC5466: $-- > 2^{nd}P$ Candidate: environment (indirect) + "global" combination
$'83 - '85$	Peterson	rotation observed: M13 fast? M3, NGC 288 slow?
$'85 - '89$	Iben, Tutukov, Bailyn et al.	BHB stars: from binary mergers??
$'85 - '95$	Zinn, ApJ 293, 424; Armandroff, Demarque, Lee, Sarajedini, Carney, King, Chaboyer et al.	"global" vs. "non-global" $2^{nd}P$ "global": depends on Galactocentric distance the only (dominant) global $2^{nd}P$: AGE
$'88 - '93$	Djorgovski, King, Piotto, Bailyn, Grindlay, Stetson, et al.	Color/population gradients Segregation? Interactions?
$'88 - '96$	Crocker, Rood, O'Connell Dorman, Renzini, Greggio, etal.	HB: Multiple populations?? HB and UV flux etc.
$'88 - '92$	Fusi Pecci, Renzini, Ferraro	Blue Straggler descendants on the Red HB??
$'88 - '96$	Fusi Pecci, Bellazzini, Ferraro Buonanno, Corsi, Rood, et al.	Environment and blue HB tails new HB observables + parametrization
$'89 - '93$	Bolte, Green, Norris, Dickens VandenBerg, Bolte, Stetson, Sarajedini, Demarque, King	NGC 288/362: $-- > 2^{nd}P = $ AGE Age: "horizontal" method
$'89 - '94$	Stetson, Ortolani, Gratton Buonanno, Corsi, Ferraro, et al. Richer, Fahlman	Pal 12: YOUNG based on MS-TO Rup 106, Arp2, Ter 7, IC4499: YOUNG based on "vertical" method
$'90 - '94$	Zinn, Armandroff, Lee van den Bergh, Hesser, Majewski, Freeman, Sarajedini, et al.	sub-systems in the GGC system: Young, Old; Halo, Disk, etc. observables: kinematics, metallicity + clock: HB-morphology (2nd P = age)
$'88 - '95$ $'93 - '95$ $'93 - '95$	Kraft et al. Rich, Liebert, Minniti Catelan, Freitas de Pacheco Rood, Ferraro, et al.	O, Na, Al, etc. peculiarities Metal rich GGCs: UV-excess NGC 288/362: revisited HB(N2808) = HB(N362)+HB(N288) Age cannot be the "only" $2^{nd}P$

tab. 1 - continued

years	reference	clue
$'91$	Preston, Shectman, Beers Suntzeff, Kinman, Kraft,	"HB-morphology" for field stars RR Lyrae and HB-morphology
$'92$	Lin, Richer	YOUNG GGC's: captured ??
$'94 -' 96$	Ibata, Gilmore, Irwin Mateo, Sarajedini, Layden, et al.	Sgr dSph merging with the Galaxy carrying its own GC system? young globulars: Ter 7, Arp 2, etc.?
$'95$	Bailyn, ARAA 33,133	review: Binaries in GGCs environment and stellar evolution
$'94 -' 96$	Ortolani, Renzini, Barbuy, etal.	HST Photometry of bulge GGCs: they are old, like 47 Tuc
$'95$	Minniti	bulge GGCs vs. disk GGCs
$'94 -' 96$	Richer et al. ApJ 463,602 Vandenberg et al. '96, ARAA, 34 Stetson et al. '96 PASP in press Bolte, et al. van den Bergh '96, PASP 108,986 Buonanno et al.	HST Photometry of remote halo GGCs: despite their red HB morphology, they display the same age as the inner halo GGCs of the same metallicity: age cannot be the dominant $2^{nd}P$ $--->$ the trend of HB-morph. with Galactocentric distance cannot be straightforwardly interpreted as an age gradient
$'96$	Buonanno et al.	dense environment and Blue Tails are correlated
$'96$	Sosin, Djorgovski, Piotto, King Liebert, Rich, Dorman et al.	HST photometry of bulge clusters: extended Blue Tail in metal-rich populations
$'96$	Sweigart	New HB models: with extra-mixing $2^{nd}P$: Helium (+ rotation?) ?